

Investigating Traffic Avoidance Maneuver Decisions of Unmanned Aircraft Pilots

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For unmanned aircraft to share airspace with manned aircraft, extensive testing is first required to ensure that such vehicles can fly safely with manned traffic. Safe operation includes not only avoiding collisions with other traffic but also complying with the Federal Aviation Regulations to remain “well clear” of other traffic. One method for investigating the safety of unmanned aircraft operations is fast-time Monte Carlo simulation of encounters between unmanned and manned aircraft. As part of that simulation, one must model how the pilots of unmanned aircraft react to the encounters. To that end, a stochastic model of realistic responses of unmanned aircraft pilots is being built. A preliminary model was formulated based on a review of existing literature on pilot decision-making, and Human-in-the-Loop experiments are being used to improve the model’s representation of unmanned pilot responses and parameterize its stochastic elements. This paper summarizes the first of those experiments, conducted in July 2015, and highlights key results that inform the pilot model.

I. Introduction

In 2012, Congress mandated that the Federal Aviation Administration establish rules for the integration of unmanned aircraft systems (UAS) into the National Airspace (NAS). Doing so requires the development of policies, procedures and equipment to ensure that operations within the NAS can be conducted safely. Existing aviation regulations require that aviators “see and avoid” nearby traffic. Without a pilot in the cockpit, unmanned aircraft rely on electronic surveillance systems to locate other air traffic and relay this information to the ground control station where the pilot observes and acts on it. The Air Force’s Common Airborne Sense and Avoid⁴ (C-ABSAA) program is developing and testing Detect and Avoid (DAA) technologies that will help the remote pilot fly the aircraft safely. Furthermore, the C-ABSAA program is supporting the work of the RTCA Special Committee 228 (SC-228) to identify minimum performance requirements of a DAA system. These initial minimum performance standards rely on the remote pilot to determine and execute an escape maneuver, rather than an automatically determined and executed maneuver response.

A standard tool for testing the safety and effectiveness of these technologies and requirements is modeling and simulation. Fast-time Monte Carlo simulation facilitates cost-efficient testing of numerous equipment configurations, pilot responses, and encounter types. For these fast-time Monte Carlo simulations to address the effectiveness of DAA with a pilot-in-the-loop, one must model how unmanned pilots respond when encountering other air traffic. Safe

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⁴ The term “sense and avoid” has evolved to “detect and avoid”; the latter term will be used throughout this paper except with regard to the C-ABSAA program.

operation in the NAS includes not only avoiding a collision with another aircraft but also maintaining what is considered a safe distance from other aircraft—“well clear” in regulatory terms [1]. Maneuvering the unmanned aircraft to remain well clear gives the pilot much more leeway than an urgent collision situation, so the model of the pilot’s responses must address this decision-making process.

A review of published literature [2-7] found little about the behavior of unmanned aircraft pilots which is not surprising given the relative novelty of such aircraft. There is, however, a relatively large body of work on the behavior of pilots of manned aircraft. Much of this literature outlines the results of human-in-the-loop laboratory experiments. The individual studies report disparate results, but synthesizing the results of these studies suggests the following maneuver preference trends:

- Single-axis vertical or horizontal maneuvers (e.g., climb) are preferred over multi-axis maneuvers (e.g., climb and turn together).
- Vertical maneuvers are preferred over horizontal maneuvers.
- No preference between right and left turns regardless of right-of-way rules⁵.
- Airspeed maneuvers are not preferred.

One finding of interest by Thomas and Wickens [7] was that the method of controlling the ownship aircraft had a moderating influence on the preference for single-axis maneuvers and the preference for vertical maneuvers. Unlike most other studies, their experiment had pilots controlling their aircraft through a “strategic route planner” where rather than identifying how the aircraft should maneuver they were to edit the desired flight path by adding or changing waypoints. Some large unmanned aircraft such as the RQ-4 Global Hawk and its variants are flown in just this manner—the pilot in the ground control station has no traditional flight controls, and the aircraft determines how to maneuver based on the pilot’s instructions of where to go—thus their observations may be relevant for modeling a UAS pilot.

Another resource that informed the development of a pilot model was flight regulations, which describe how pilots should react in some circumstances to ensure a complementary maneuver for both aircraft in a conflict. The Federal Aviation Regulations, 14 CFR Section 91.113 [8], describes right-of-way rules for aircraft and how they should maneuver to avoid one another, with right-hand turns encouraged. If the goal of the UAS pilot is to avoid loss of well clear, one must ask whether maneuvers to achieve that goal are covered by the right-of-way conditions in the FAR. The rules are simple, but the studies above found little preference for right-hand turns regardless of the general applicability of these rules. In addition, the final clause in the section, “unless well clear,” introduces ambiguity into the rules because “well clear” is subjective and could depend on the context of the (non-critical) situation.

Due to the limited data on the behavior of UAS pilots, two studies were conducted to support model development: first, a comprehensive survey eliciting feedback from pilots on their preferences for decision making regarding maneuvering to avoid traffic, the goal of which was to qualitatively inform an initial structure for the model; second, a human-in-the-loop experiment which examined how pilots actually responded when confronted with various traffic situations. The data collected during the second study is being used to update the model structure and to characterize variability in the decision parameters.

One of the main limitations of prior studies was sample size. To maximize the number of participants in the experiment, while being cognizant of the limited availability of UAS pilots, a low-fidelity “desktop” simulator was selected that was easy to transport, thereby allowing the simulation to be brought to the pilots.

A second limitation observed in the literature was a tendency for homogenous populations—for practical reasons, often groups of aviation students from a single flight school. Previous studies [9] suggest that maneuver preferences depend on the type of UAS the pilot operates, perhaps due to the dynamic limitations of that particular aircraft or procedures reinforced in flight training for that aircraft. To capture responses from a variety of UAS pilots, a population was selected that includes individuals with experience flying a range of medium to large UAS (such as Predator, Reaper and Global Hawk).

⁵ The FAA regulations encourage right-hand turns, specifically for converging aircraft “When aircraft of the same category are converging at approximately the same altitude (except head-on, or nearly so), the aircraft to the other’s right has the right-of-way, for head-on approaches “When aircraft are approaching each other head-on, or nearly so, each pilot of each aircraft shall alter course to the right” and for overtakes “ach aircraft that is being overtaken has the right-of-way and each pilot of an overtaking aircraft shall alter course to the right to pass well clear.” Per Federal Aviation Regulations, 14 CFR Section 91.113.

II. Operational Context

Established in 2013, RTCA SC-228 is working to develop the Minimum Operational Performance Standards (MOPS) for DAA equipment to be used with unmanned aircraft. The pilot model must fit within the context of the SC-228 DAA MOPS to be useful towards identification of system requirements. Key operational concepts of the DAA system from the vantage of pilot modeling are summarized here.

The DAA MOPS currently being drafted by SC-228 describe the overall DAA system environment and clarifies the many interoperating components of the system. The perspective of an individual unmanned aircraft pilot is somewhat simpler. The pilot sits in a Ground Control Station (GCS) at a workstation including aircraft controls and a DAA display. The DAA display indicates air traffic in the vicinity of the unmanned aircraft as perceived by surveillance systems onboard the unmanned aircraft—either from cooperative systems like the Traffic Alert and Collision Avoidance System (TCAS) that use information broadcasted by other aircraft or from non-cooperative sensor systems such as primary radar that scan the surrounding airspace for other traffic. Communications between the pilot and the unmanned aircraft may be by direct radio link or satellite link. The pilot is also in voice communication with Air Traffic Control (ATC) services to coordinate any course changes.

A. Well Clear Definition

Fundamentally, the purpose of the DAA system is to allow an unmanned aircraft to meet the regulatory requirements to “see and avoid” other aircraft, by remaining “well clear” of other aircraft. UAS will “see” with electronic surveillance. Once aircraft is “seen,” it must be determined what constitutes well clear. Federal regulations pertaining to aviation provide no specific definition of this term; it is left to the pilot’s judgement. Thus one of the first challenges faced in developing requirements for DAA systems was to establish a measurable, quantitative definition. This was accomplished by a panel of subject matter experts (as documented by Cook et al. [1]) and subsequently adopted by the SC-228. That definition states that aircraft are well clear if **any** of the following conditions are true:

- 1) Modified-tau is greater than 35 seconds.
- 2) The predicted horizontal miss distance (HMD) is greater than 4000 feet.
- 3) The current vertical separation is greater than 450 feet.

In this definition, modified-tau is a metric of time-to-go to the closest point of approach in the horizontal plane and is defined as

$$\tau_{\text{mod}} = \begin{cases} \frac{\text{DMOD}^2 - R^2}{R\dot{R}} & \text{if } R > \text{DMOD}, \dot{R} \leq 0 \\ 0 & \text{if } R \leq \text{DMOD} \\ \infty & \text{if } R > \text{DMOD}, \dot{R} > 0 \end{cases} \quad (1)$$

where R is the horizontal range, \dot{R} is the range rate, and $\text{DMOD}=4000$ feet.

If at any time **all** three conditions are **not** true, a well clear violation (WCV), also referred to as a Loss of Well Clear (LoWC), has occurred.

B. Alerting






To prompt the pilot that some action may be needed to prevent a WCV, SC-228 has adopted an alerting scheme that indicates conflicting air traffic with color-coded icons and, in some cases, an aural alert signal. Alert criteria are based on projected penetration of an alert region, defined similarly to the well clear violation region, within a certain look-ahead time. The alert level increases as the proximity to a WCV increases. Projected ownship and intruder states are found by constant velocity extrapolation of the current state. The alerting scheme used in this study is summarized in Table 1. Note that SC-228 has continued to evolve the alerting scheme in the time since this experiment was conducted; in particular, the proximate traffic advisory has been eliminated and the threshold values have been revised.

Alerting also factors into the concept of operations. Ordinarily the pilot of the UAS is required to clear any maneuvers off-course with ATC; however, under a Warning Alert pilots are permitted to maneuver without prior ATC approval.

C. Display Requirements

A pilot in the cockpit relies on his or her eyes, communication with ATC, and perhaps supported by a cockpit traffic display to see and avoid other air traffic. For the pilot of an unmanned system, electronic surveillance replaces eyes and the traffic display becomes the primary view of nearby air traffic. As defined by SC-228, traffic displays can be grouped into three categories depending on the amount and type of information shown and the level of decision support offered. The most basic display is termed an informative display—it shows air traffic on a map and provides basic information about each aircraft like airspeed, vertical rate, and call sign. It provides no explicit maneuver

Table 1. Alerting scheme used to warn study subjects of nearby air traffic.

Alert Level	Alert Type/Criteria	Aural Alert	Symbol
0	None	None	
1	Proximate Traffic Advisory <ul style="list-style-type: none"> 85-second look-ahead time 35-second modified tau 1.5-nm HMD/DMOD, 1200-ft vertical separation 	None	
2	Preventive Alert <ul style="list-style-type: none"> 75-second look-ahead time 35-second modified tau 1-nm HMD/DMOD, 700-ft vertical separation 	Tone	
3	Corrective Alert <ul style="list-style-type: none"> 75-second look-ahead time 35-second modified tau 0.75-nm HMD/DMOD, 450-ft vertical separation 	Tone	
4	Warning Alert <ul style="list-style-type: none"> 25-second look-ahead time 35-second modified tau 	Tone	

guidance to the pilot. A suggestive display adds to this some indication of a range of possible maneuvers to avoid a conflict. Finally, a directive display gives the pilot a specific maneuver to resolve a conflict (e.g., a resolution advisory (RA) from TCAS).

To determine the display type needed for DAA systems, a series of human-in-the-loop experiments were conducted for SC-228 (separate from the experiment described here) examining how well pilots could stay well clear while using various display concepts [10,11]. These experiments demonstrated that pilots were best able to maintain separation if the display indicated safe maneuver choices (the suggestive displays) than if shown only traffic information. In light of these findings, SC-228 adopted suggestive guidance as a minimum requirement for a DAA system.

III. Pilot Survey

The first step in identifying how unmanned aircraft pilots would respond in air traffic situations was to conduct interviews. A survey was developed with a total of 25 questions in several formats (e.g., multiple choice, agree-disagree, free response) to probe various aspects of the maneuver decision to include what sources of information they rely upon, what their first choice of maneuver direction would be, how far in advance of the conflict they prefer to maneuver, and how they interact with ATC. The survey began by explaining the quantitative well clear definition and other terms. The respondents were instructed to answer the questions as though they were flying an unmanned aircraft in the NAS under instrument flight rules (IFR), in radio communications with ATC, and with a traffic display highlighting traffic within 80 seconds of a well clear violation.

The survey was distributed to military unmanned aircraft pilots, and a total of 23 responses were received. The following summarizes noteworthy results:

- Most pilots typically assessed potential conflicts by distance to point of closest approach rather than time.
- When contacting ATC to coordinate a maneuver, most request a specific heading or a specific altitude rather than just a maneuver direction.

- Time to closest point of approach, distance to closest point of approach, and vertical separation were identified as the most useful information for deciding when to maneuver.
- Distance to closest point of approach, vertical separation, and ATC clearance were identified as the most useful information for deciding how to maneuver.
- If encountering traffic while climbing or descending, most preferred to level off to avoid a conflict.
- If encountering traffic while in level flight, a slight majority (60%) preferred to avoid the conflict by turning.

IV. Human-in-the-Loop Experiment

The stated preferences collected with the Pilot Model Survey were useful towards establishing a general architecture of the pilot model. However, to actually parameterize the model, quantifiable revealed preferences were collected through a Human-in-the-Loop (HITL) experiment in which pilot subjects were asked to fly a generic unmanned aircraft in a simulator and maneuver to avoid nearby air traffic.

A. Basic Assumptions

To be consistent with the SC-228 concept of operations and minimum requirements, a display with suggestive guidance was used to inform the UAS pilots' decision making with ATC providing clearance of maneuver requests. Pilots were informed that all encounters would be one-on-one, at altitudes below 10,000 feet, and that the intruder was noncooperative (i.e., flying without a transponder turned on and not communicating with ATC).

B. Simulator

The experiment was conducted using a portable aircraft encounter simulator and pilot workstation provided by the U.S. Air Force Simulation and Analysis Facility (SIMAF). The pilot interface is built around SIMAF's simulation software of the dynamic response of the ownship aircraft to pilot command inputs. Without intervention from the pilot, the ownship follows a predetermined flight path. The intruder aircraft and all background traffic follow predetermined trajectories.

The pilot workstation comprised two monitors, shown in Figure 1, a keyboard and a mouse. The left-hand monitor showed a moving map and the Primary Flight Display (PFD) with the aircraft's attitude, heading, altitude, and speed. The pilot's ATC communication controls and ability to declare all clear (i.e., end the simulation) were also found on the PFD. The right-hand monitor, the DAA display, showed nearby traffic and suggestive guidance.



Figure 1. Multifunction (left) and Detect and Avoid (right) display comprising the UAS pilot's workstation

Several pilot aids, consistent with SC-228 requirements (as of March 2015), were incorporated in the interface to help the participant negotiate traffic in the experiment. First, a succession of visual and aural alerts was used to warn pilots of nearby aircraft that may cause a well clear violation. The alert levels and the conditions that trigger them were summarized earlier in Table 1.

In addition to alerts, the Omni Bands suggestive guidance algorithm, part of the Java Architecture for DAA Modeling (JADEM) software suite developed at NASA Ames Research Center and provided by NASA for this study [12], was used to display the predicted alert level if the pilot were to turn, climb, or descend—in other words, to suggest maneuver alternatives that the pilot could employ to resolve the conflict. The same suggestive guidance was

used as one of the concept displays in the NASA Part Task 5 (PT5) experiment as described by Rorie et al. [10]. NASA's experiment showed that pilots were more successful at avoiding well clear violations when given suggestive guidance. This finding led to the SC-228 decision that suggestive guidance be a minimum requirement for DAA displays noted above.

Table 2. Omni Bands suggestive guidance color-coding.

Alert Level	Color	
	Heading Bands	Altitude Bands
0 – None	Green	Green
1 – Proximate Traffic Advisory	Green	Green
2 – Preventive Alert	Dashed Yellow	Green
3 – Corrective Alert	Yellow	Yellow
4 – Warning Alert	Red	Red

Omni Bands heading suggestions took the form of one or more colored arcs (“bands”) on the traffic display's compass rose and an altitude tape to the right of the compass rose. The “Fly/No Fly” bands were colored-coded to indicate the threat level severity given a particular heading, as shown in Table 2. For example, a green band meant that flying that heading would not lead to any alerts (preventive, corrective or warning). Unlike directive guidance from systems such as TCAS, the pilot was not required to follow suggestive guidance; it was intended to help the pilot with decision-making. Take note in the table of a difference between the heading bands and altitude bands: a predicted preventive-level alert is colored dashed-yellow in heading but green in altitude.

Suggestive guidance for the vertical plane was shown with a column of colored bands on the right side of the traffic display. Each band corresponds to altitudes above and below the ownship's current altitude in increments of five hundred feet. See Figure 2 for an example of the Omni Bands suggestive guidance from our DAA display.

Maneuvers were commanded by entering the desired heading and/or altitude in text boxes on the PFD and clicking an ‘execute maneuver’ button—similar to the strategic route planner mentioned previously. Pilots could choose a horizontal maneuver, a vertical maneuver, or both and were permitted to make as many successive maneuvers as



Figure 2. Heading bands shown on inner range ring (left) and altitude bands (right). In this example, pilot can turn right $>5^\circ$ to be alert free, descend to 2,000 ft. to be alert free, or maintain course or turn left $>60^\circ$ for a preventive alert

desired. Horizontal maneuvers were executed at $3^\circ/\text{s}$ and vertical maneuvers at 500 fpm with a generic ownship dynamic model, consistent with the SC-228 assumptions.

Pilots were trained to coordinate with ATC prior to maneuvering if possible via simulated ATC interaction. When ready to maneuver, the pilot clicked a button on the PFD, and after a delay drawn randomly from a gamma distribution with mean 11 seconds (fit to ATC coordination times from NASA's PT5 experiment) a message was displayed indicating that the pilot may proceed. There was no voice communications and all maneuver requests were approved. Flight controls were not disabled during this delay, so the pilot was able to command maneuvers before receiving authorization.

C. Encounters

Twenty-two single intruder encounters were selected from a larger set generated using the MIT Lincoln Laboratory developed uncorrelated encounter model [13] for evaluation of a preliminary pilot model. The UAS was assumed to be on an IFR flight plan heading due north in all encounters. All encounters occurred in Class E airspace below 10,000 feet with a noncooperative intruder: i.e., one whose maneuvers were not coordinated with Air Traffic Control or the UAS pilot. Eighteen encounters included a nonmaneuvering intruder; the remaining four encounters included scripted maneuvers by the intruder. Encounter types included head-on, converging (horizontally and/or vertically), and ownship overtaking. All encounters included one or more alerts; however, three encounters require no pilot input to remain well clear. Encounters began when the two aircraft were 10 nautical miles apart, which was usually well ahead of the earliest alert. Depending on encounter geometry, encounters lasted from two to eight minutes.

Scripted background traffic was included in the encounters to force the pilots to identify the threatening traffic. However, because the model is intended for single intruder encounters, the background traffic was far enough away from the encounter of interest that it was unlikely to influence the pilot's maneuver decisions.

D. Procedures

The experiment was conducted one pilot at a time. Each test commenced with a training briefing to explain the controls, display, operational procedures (e.g., coordinating maneuvers with ATC) and the objective of avoiding well clear violations while minimizing course deviations. After the training briefing, the pilot was guided through several training encounters for hands-on familiarization with the displays and controls before beginning the test.

To explore the relationship between alerts and a pilot's decision to maneuver, the test encounters for each pilot were divided into two equal blocks. In one block of encounters, pilots were to maneuver only after an alert. In the other block of encounters, pilots were free to maneuver at will: that is, at their discretion and best judgment without having to wait for an alert. Pilots were unaware of whether they would be maneuvering at will or waiting for an alert until just prior to the encounter block being introduced and trained. The order of the blocks, the encounters contained in each block, and the order of the encounters within each block were varied from pilot to pilot to preclude any potentially confounding training effects. For flexibility, the runs were balanced for groups of six pilots. The total test time, including training, each block of encounters with a break in between, and a brief post-test survey, was approximately 2.5 hours.

E. Test Subjects

A relatively heterogeneous group of 26 test subjects were recruited for the study. All test subjects were current or recent UAS pilots from the following duty stations:

- Eight from Edwards Air Force Base
- Four from Beale Air Force Base
- One from Wright-Patterson Air Force Base
- Seven from Springfield (OH) ANG

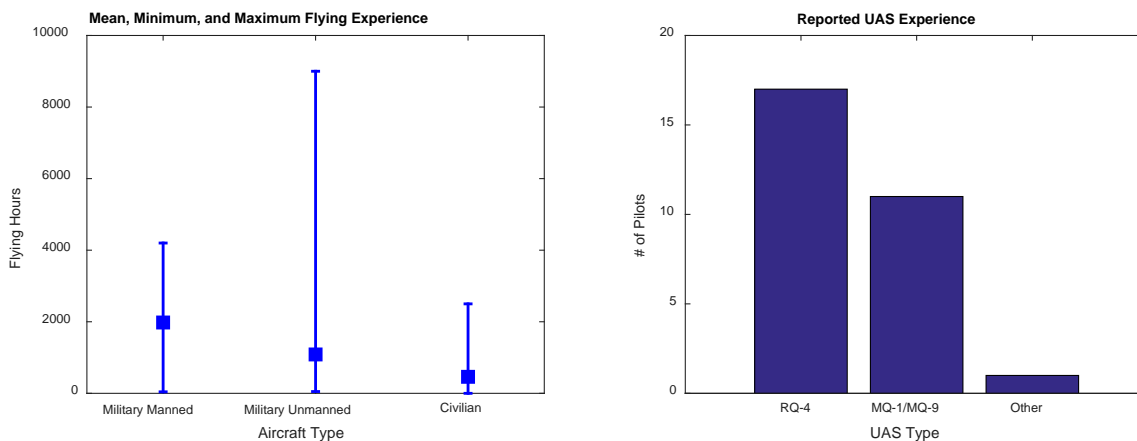


Figure 3. Flying experience of UAS pilots participating in the study.

- Two from Grand Forks (ND) ANG

- Three from NASA Armstrong Flight Research Center
- One from MIT Lincoln Laboratory

Figure 3 gives a more detailed demographic breakdown of the pilots.

V. Results

Overall, the pilots were generally successful at remaining well clear: out of a total of 572 encounters tested, there were no near mid-air collisions (defined as separation of less than 500 feet horizontally and 100 feet vertically), only 12 well clear violations. Seven of those well clear violations were a result of intruder maneuvering. Pilot feedback after the experiment indicated that the displays provided adequate information to maintain separation and that their training was sufficient.

Figure 5 shows the recorded responses of all pilots for the first encounter. It is clear that there is significant variability in maneuver timing, maneuver direction, and maneuver magnitude.

Pilots were permitted to maneuver as often as they wanted, and the data was separated into the first maneuver (categorized as the initial maneuver) and any subsequent maneuvers (categorized as update maneuvers). Pilots executed a total of 838 maneuvers throughout the test. There was at least one maneuver in every case, so there were 572 initial maneuvers and 266 update maneuvers.

Pilots almost universally complied with instructions to coordinate their traffic avoidance maneuvers with ATC.

A. Maneuver Timing

The maneuver timing results indicated a marked difference in the pilot's decision of when to maneuver between the two conditions, wait for an alert versus maneuver at will. Given the freedom to do so, as shown in Figure 4, the pilots frequently maneuvered away from the intruding traffic before an alert. In 62% of "maneuver at will" encounters the initial maneuver occurred before the first aural alert (preventive or corrective alert, depending on the encounter). We concluded that, lacking any disincentive, pilots would generally prefer to maneuver upon identifying a potential conflict with another aircraft whether or not an alert has been issued.

Among encounters with the initial maneuver after the first aural alert, the average time from the alert until the pilot contacted ATC was 6.2 seconds. Examining the response times by encounter revealed that responses were typically slower in encounters in which the ownship and/or intruder was climbing or descending. The average response time in those encounters was 8.6 seconds while the average response time for encounters with level ownship and intruder was about half that at 4.4 seconds, a significant difference with $p < 0.01$.

Since pilots maneuvered in every encounter, we could not determine the encounter characteristics motivating a decision not to maneuver.

B. Maneuver Direction

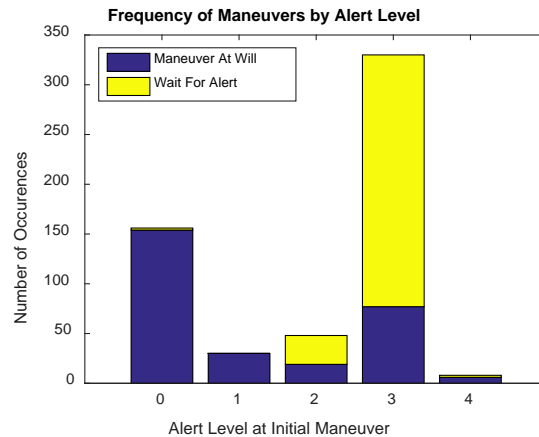


Figure 4. Alert level at initial maneuver over all encounters.

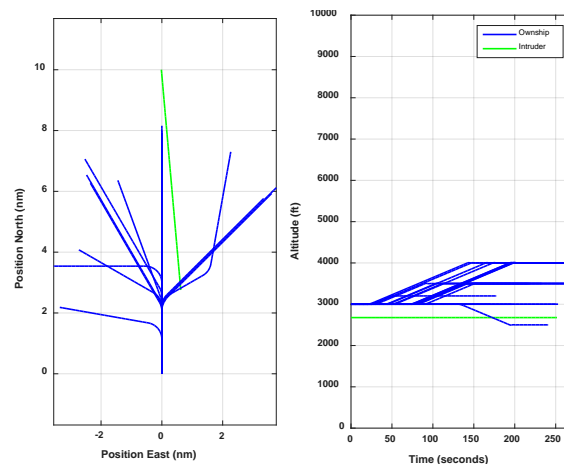


Figure 5. Ensemble of pilot responses to encounter #1.

Figure 6 shows the overall breakdown of maneuver choices by maneuver plane, revealing that multi-axis maneuvers ('combo') were substantially less common than horizontal or vertical single-axis maneuvers, consistent with earlier studies noted above. Breaking these results down further, one key finding is a clear distinction between the initial maneuvers selected prior to alert and the initial maneuvers that occurred after alert: the former group showed much greater preference for vertical maneuvers. The latter group instead showed statistically significant preference for horizontal maneuvers over vertical maneuvers ($p < 0.01$)—see Figure 7. Furthermore, there was a significantly greater preference for multi-axis maneuvers when the initial maneuver occurred after alert. Figure 8 compares maneuver preferences for initial maneuvers with those for update maneuvers over all encounters.

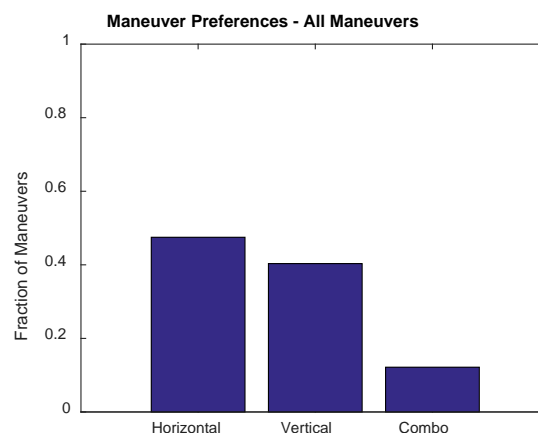


Figure 6. Overall maneuver direction choices (N=838).

Grouped this way, a marked preference for turns in update maneuvers is evident while there is not a significant preference for initial maneuvers. We expect this relates to the dynamic capabilities of the ownship—when close to well clear violation, its low maximum vertical rate make horizontal maneuvers more efficacious. Of further note in Figure 8, multi-axis maneuvers were rarely used for updates.

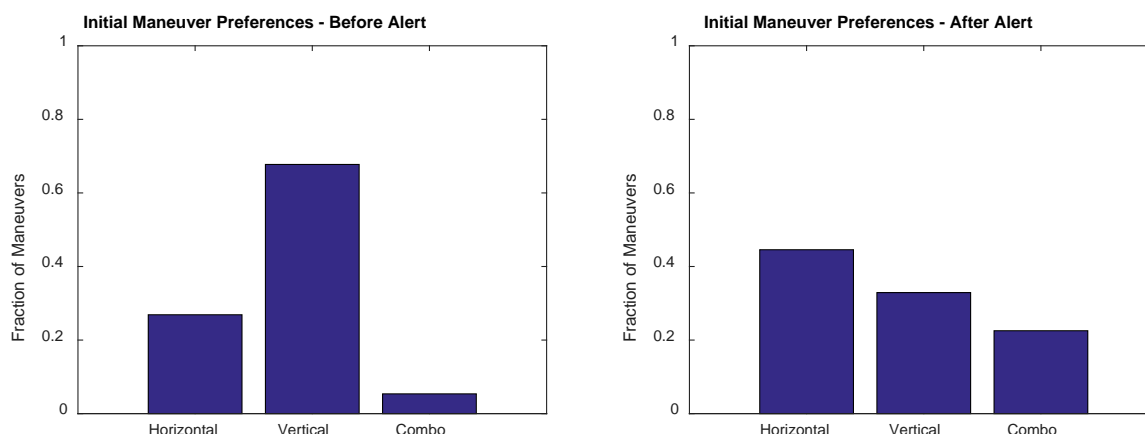


Figure 7. Maneuver plane preferences for initial maneuvers executed before an alert (left, N=186) and after an alert (right, N=386).

Among vertical maneuvers, there was a strong preference for climbs over descents ($p < 0.01$). However, the encounter geometry may play a role in that bias because the intruder is level with or below the ownship in all but one of the level-level encounters and in many of the encounters the ownship's altitude is 3000 feet. Since the pilots were experienced at flying UAS to much higher altitudes it is possible that this was their preference and they were wary of descending too low for traffic avoidance.

Among all of the horizontal maneuvers, there was a small but statistically significant preference ($p < 0.03$) for left turns over right. This preference is surprising because the right-of-way rules generally favor right-hand turns. Of particular note, the pilots in this experiment strongly favored left-hand turns in head-on encounters, turning to the right per the right-of-way rules in only 29.6% of those encounters. We believe this has to do with the particular encounter geometries faced by the pilots. Encounters were categorized as head-on when the bearing of the intruder was within 10° of the ownship's heading and the bearing of the ownship was within 10° of the intruder's heading. All of the so-designated encounters were slightly skewed and not directly head-on (i.e., opposite headings on collision course). Consequently, pilots may have mentally projected the intruder's trajectory forward and found that turning to the left was safer than to the right. It is not certain whether the pilots considered the right-of-way rules in reaching a decision. (The pilots were not explicitly instructed to follow right-of-way rules.)

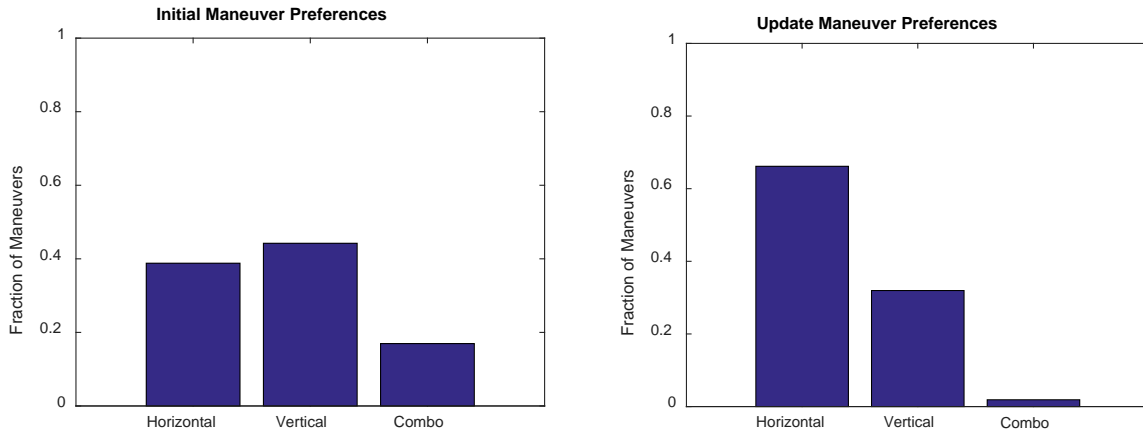


Figure 8. Maneuvering plane preferences for initial maneuvers (left, N=572) and update maneuvers (right, N=266).

We also observed that the direction of maneuver per axis correlates well with the Omni Bands suggestions. When pilots did turn, about 75% of the time it was in the direction of the smaller maneuver suggested by Omni Bands (e.g., left if green is displayed for headings greater than 30° to the left and 45° to the right).

C. Maneuver Magnitude

Figure 5 displayed the wide range of maneuver magnitudes selected by the pilots to just one encounter. Examining maneuver magnitudes across all encounters revealed no discernable pattern. However, plotting the maneuver magnitude choices relative to the smallest maneuver suggested by Omni Bands in the direction of the maneuver reveals a gamma-like distribution (see Figure 9). Pilots usually selected maneuvers 10-30° or 500-1000 ft larger than the Omni Bands suggestion, but in the distribution tails we see evidence of the abundantly cautious and the overly aggressive pilots alluded to in Section 1.1. In fact, some of the maneuvers selected were smaller than the Omni Bands suggestion. There are several potential explanations for this. First, the pilot may have simply misread the guidance. This is mostly likely for horizontal maneuvers as the suggestions are given in 1° increments but the compass is graduated in 45° increments (see Figure 2). Second, the guidance may have changed between when the pilot selected his maneuver and when it was executed. Third, the pilot may not have been actively using the suggestive guidance. This is more likely for vertical maneuvers as the guidance is shown on the side of the DAA display; in fact, several pilots noted that it was hard to see the altitude bands when they were focused on the ownship and intruder tracks shown towards the center of the display. Finally, the horizontal extent of the alert region is larger than the extent of the WCV region (0.75 nm vs. 0.66 nm), so a pilot could choose to maneuver to a heading that will result in an alert but not a WCV.

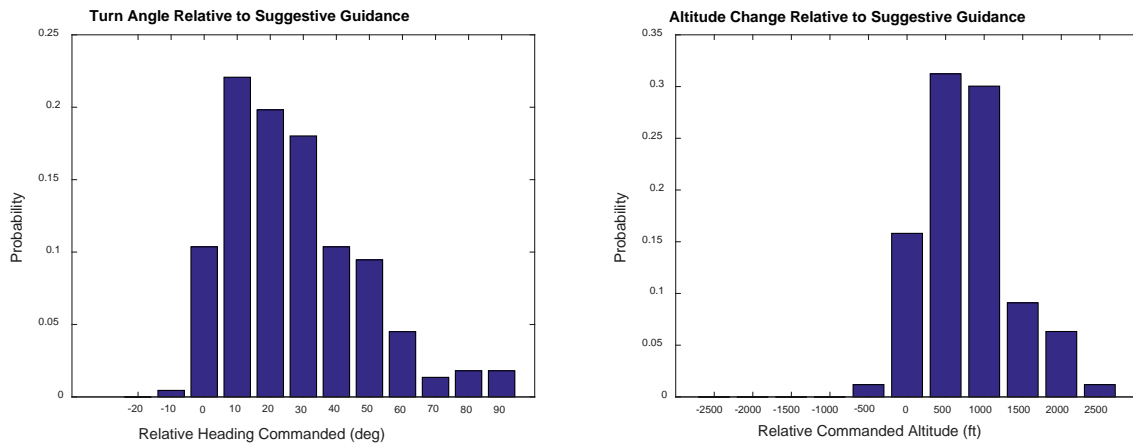


Figure 9. Maneuver magnitudes selected relative to the magnitude of the smallest OmniBands suggestion.

D. Post-test Survey

At the end of all trials, each pilot participant completed a brief post-test survey. The primary purpose of the survey was to ensure the validity of the data collected. In fact, the pilots reported almost unanimous strong agreement to questions about whether they had the training and the information to be able to maintain separation and minimize course deviations. However, a question about whether their strategy was affected by having to wait for an alert before maneuvering elicited varied responses. This presents a challenge determining the appropriate triggering mechanism for the pilot model, and it suggests a conflict that must be addressed in a final concept of operations. Many pilots also responded that they felt the suggestive guidance had not strongly influenced their decision-making, while above we noted a compelling correlation between the actual responses and the suggestive guidance.

VI. Future Work

This dataset will form the foundation of an empirically based stochastic operator model. Immediate modeling goals are to update an existing heuristic model with preferences observed in the data; in the longer run, machine learning techniques will be employed to more fully explore the dataset and identify correlations between encounter features and pilot decisions.

Further HITL experimentation is planned to enhance fidelity and focus on particular situations of interest. Additional situational features that may influence pilot behavior will be considered including:

- Imperfect surveillance.
- More extensively maneuvering intruders.
- More realistic procedures (e.g., requiring a return to course).
- Differing ownship dynamic capabilities representing specific UAS (e.g., Predator vs. Global Hawk).

VII. Conclusion

This HITL experiment provided a rich set of data from which to build a model of unmanned aircraft pilots' responses to nearby air traffic. The experiment has identified several characteristics of UAS pilot responses that might be considered for that model. First, pilots seeing a conflict coming would prefer to maneuver even earlier than the alert timeline used in the experiment. Second, pilots responding before an alert when guidance was displayed prefer to maneuver in the vertical plane while those closer to the conflict tend to pick either a horizontal maneuver or a horizontal/vertical combination maneuver. Third, response time slows when the ownship and/or intruder is climbing or descending. The data collected provides evidence of pilot response under many encounter conditions; however, further experimentation is necessary for more definitive answers to some questions. In particular, more work is required to probe pilot responses when they are very close to a well clear violation.

It is important to note that few pilots of unmanned aircraft have experience with UAS DAA systems or contending with other air traffic because UAS operations in the NAS are currently authorized by special exception only. The responses recorded in this experiment are thus responses to an unfamiliar task. UAS pilot behavior may evolve as operation of UAS in the NAS becomes more common, and DAA systems are fielded with new policies, procedures, and training.

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